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Computational and fMRI Studies of Visualization

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Background

Functional brain imaging has progressed far beyond just identifying and cataloguing the brain areas that activate in a task. As of about 6 years ago, this project proposed to bring a new technology, fMRI, to the service of understanding spatial cognition. The task has involved developing new methodologies, mastering a new, evolving technology, and synthesizing the several sub-disciplines of neuroimaging, neuroanatomy, and neurophysiology. But as the report below indicates, the progress has been considerable. We are obtaining important results, publishing the studies in first-rate journals, and presenting the data in talks to diverse audiences. The results from this project and many others are being incorporated within the developing theory, so that the progress is more than a collation of findings, but an integrated body of knowledge with underlying principles for extensibility and application. Correspondingly, the theory, methodological approach, and the ongoing projects are beginning to influence the fields of cognitive psychology and cognitive neuroscience.

1. IMAGERY, SPATIAL WORKING MEMORY, AND COGNITIVE STRATEGIES

Volumetric modulation and dynamic recruitment of neural activation One of the cortical network properties that we have extensively explored is the volumetric modulation of the brain activation as a function of the cognitive processing. For example, in studies requiring the mental rotation of an object, the amount of fMRI-measured activation increases with angular disparity (Carpenter et al., 1999 in *J. of Cognitive Neuroscience*). We interpret the volumetric properties as reflecting the ratio of the task's demand for cognitive resources to the supply, or capacity utilization. Similarly, in studies requiring the mental tracking of the location(s) of one or three targets in a 2-D or 3-D visual array, the volume of the brain activation increases both with the number of items to be tracked and the dimensionality of the space (3-D elicits a greater volume). Moreover, the two effects (that of number of targets and dimensionality) are not localized to single parts of the brain, but occur in both the prefrontal cortical regions and the parietal regions, indicating extensive collaboration between the members of the spatial network. Several articles on volumetric modulation during spatial thinking have been published or are in press.

Imagery. One very recent fMRI study examined how people mentally rotate a 3-dimensional object (an alarm clock) that is retrieved from memory and rotated according to a sequence of auditory instructions. We manipulated the geometric properties of the rotation, such as having successive rotation steps around a single axis versus alternating between two axes. The latter condition produced much more activation in several areas. Also, the activation in several areas increased with the number of rotation steps. During successive rotations around a single axis, the activation was similar for rotations in the picture plane and rotations in depth. The parietal activation (plausibly one of the sites of geometric transformation computations) was very similar in this situation (in terms of location and volume) to mental rotation of a visually presented object (in a Shepard-Metzler task). However, there was much less activation in the extra-striate (ventral-stream) areas in this clock task (where there is no visual input) than in a Shepard-Metzler task (where much more analysis has to be done on a perceptually available figure). The findings indicates that mental rotation may be decomposable to some extent into the figual analysis portion and the geometric transformation portion, and that the parietal and extrastriate areas respectively underpin these two types of processes. (At the same time, functional connectivity analyses (in a submitted manuscript) indicate that there is a higher degree of synchronization between these two areas during the recognition of rotated familiar objects). So the specialization of function co-exists with the interaction of function, a property of cortical processing that is incorporated into 4CAPS models. The article describing these results are to be found in Just, Carpenter, Maguire, Diwadkar, & McMains, 2001.

Strategy differences. Most complex problems and even some seemingly simple ones admit the use of more than one strategy or processing mode, such as verbal vs. visuo-spatial. With the recent advent of neuroimaging techniques, it is now possible to examine the cortical systems that support these modes of

processing, and to understand how their behavioral characteristics relate to their neural substrates. In fact, it is possible to tell which mode a person is using. We taught participants to do a sentence-picture verification task using either a verbal strategy or a visual-spatial strategy. One objective was to examine the relation between the strategies (i.e., cognitive routines) and their underlying patterns of cortical activation using functional Magnetic Resonance Imaging (fMRI), building on existing data which suggested partial separation between the cortical systems responsible for linguistic processing and those responsible for visual-spatial processing. A second objective was to examine how the strategy-related differences in cortical activity are modulated by individual differences in cognitive skill.

The verbal strategy produced more activation in language-related cortical regions (e.g., Broca's area), whereas the visual-spatial strategy produced more activation in regions that have been implicated in visual-spatial reasoning (e.g., parietal cortex). One way of identifying which strategy or mode is being used is to count the number of activated voxels in two regions, Broca's area and the left parietal cortex, and then subtract the latter from the former. This difference should be larger for the verbal than visual-imagery strategy because the verbal strategy tends to activate Broca's area, whereas the visual-imagery strategy tends to activate the left parietal cortex. This procedure correctly identifies the strategies used for ten out of twelve (83%) participants.

These relations were also modulated by individual differences in cognitive skill: individuals with better visual-spatial skills (as measured by the Vandenberg, 1971, a mental rotation test) had less activation in the left parietal cortex when they used the visual-spatial strategy. These results indicate that language and visual-spatial processing are supported by partially separable networks of cortical regions, and suggests one basis for strategy selection: the minimization of cognitive workload. This work by Reichle, Carpenter, and Just appeared in *Cognitive Psychology.*

2. METHODS DEVELOPMENT

Functional connectivity. To progressively make the mapping closer between cognition and brain activation, it is necessary for us to continually develop new techniques and software for analyzing the fMRI data. For example, a key network property that we have been examining is called *functional connectivity* between activated brain areas; it is assessed by the correlation of the activation time-series data between voxels in different areas, a time series with an observation every few seconds. The general assumption is that the functioning of voxels whose activation levels rise and fall together is coordinated. In one analysis, the correlations are based on only those periods when the task is being performed (excluding the fixation periods), so that the time series indicates the momentary fluctuations in activation level during the actual task performance. This is a novel measure and contrasts with examining the correlation throughout the entire time course of a study, a measure which is primarily dominated by the alternation of the task with rest periods. Restricting the analysis to only the task periods essentially examines the micro-structure of the processing fluctuations. Our results show that during a spatial tracking task, the functional connectivity (i.e. degree of synchrony) between the activated voxels in DLPFC and the parietal regions reliably increases with the processing load. We have several papers published or in press that report the results of functional connectivity and more in the pipeline. For example, we have found that the functional connectivity between the parietal area and DLPFC increases with cognitive workload, indicating closer coordination among areas when the cognitive demands are higher (Diwadkar et al., 2000).

Assessing the functional connectivity among the nodes of a large-scale neural network moves fMRI-imaging toward an analysis of cognition in terms of dynamic systems. To perform these analyses, we (Vlad Cherkassky) have developed a package called VOXCOR which flexibly performs many types of correlational analyses with appropriate visualization tools to display time courses of activation in various cortical areas.

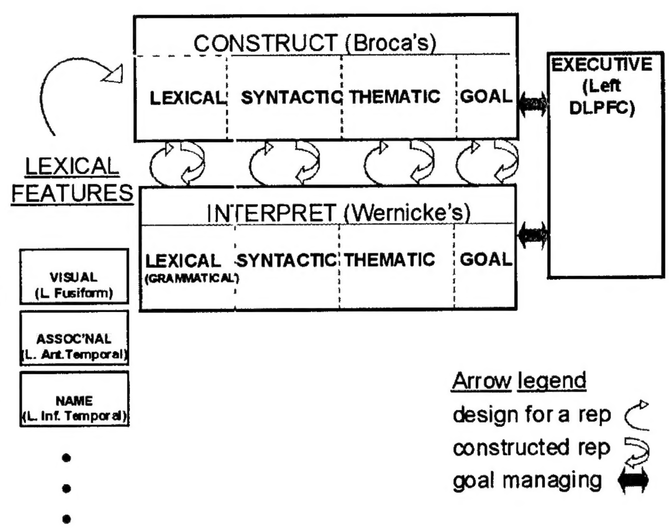
Increasing temporal resolution in fMRI. Even though fMRI measurement involves a delay between the occurrence of a given thought process and the hemodynamic response, it is nevertheless

possible to methodologically and technologically strengthen the relation between the measurement and the theoretical account. We are continuing to explore higher temporal and spatial resolution on a new fMRI scanner, which has higher capabilities than were previously available. We started this work by pushing the limits of an older scanner, and discovering linguistic effects on brain activation within about 1200 msec of stimulus onset, long before the hemodynamic response reaches its maximum value at 4-6 sec (Carpenter et al., 1999 in *NeuroImage*). With the new scanner, we are able to sample 30,000 voxels (each one about 30 mm^3) once every 500 msec, and still obtain excellent sensitivity. We are currently exploring sampling each voxel every 250 msec. The higher sampling rate does not overcome the hemodynamic delay (which has to be at least 500 msec), but it does provide a more frequent and measurement of the activation. This increased spatio-temporal resolution brings the fMRI data into closer correspondence with the theoretical account of the ongoing cognitive, as specified within the computational modeling system being developed. Within 4CAPS models, the quantum is about 50 msec, but the next level of aggregation, at about 200 or 250 msec, is perhaps even more cognitively meaningful. Thus the theory and fMRI data are approaching the similar levels of temporal granularity.

3. DEVELOPMENT OF A THEORY AND A COGNITIVE MODELING SYSTEM

As the relation between brain activation and cortical organization begins to unfold in the fMRI research, it is being incorporated into the design of 4CAPS, which is a production-system architecture with several connectionist features first reported in the Just et al., 1999 article in *Human Brain Mapping*. The theory has recently been described in a comprehensive manuscript that has been prepared for publication. It is clear that the theory and 4CAPS provide a powerful conceptual tool for understanding current results and guiding future research. The existence of the computational modeling system makes it possible to ask precise, concrete questions about performance in tasks that have not yet been examined with fMRI, some of which can never be examined with fMRI because of the technology's restrictions on motion and magnetic and electrical activity.

The computational system makes it possible to develop models of a particular cognitive task. One example is a model of sentence comprehension that accounts for the word-by-word processing times, the probability of comprehension error, and the modulation of the brain activation in several cortical areas over the course of about 24 sec. The accompanying diagram depicts each model component as a block, with each block corresponding to a cortical region. The 6 blocks correspond to the 6 left-hemisphere components of the comprehension model. The 3 lexical components are placed within a larger box. The CONSTRUCT and INTERPRET components are divided horizontally into four main parts, corresponding to the four kinds of representations the model deals with: lexical, syntactic, semantic, and goal. The arrows are intended to show the interaction between components. It is difficult in a static diagram to depict the adaptive, dynamic behavior of each component, as well as the dynamic allocation of work between the components. Some of the predictions of this model are presented in Part 4 (on development of deconvolution methods). Another example of a new 4CAPS model is one that solves the Tower of London problems. The models provide the tools to quantify and predict cognition and brain activation.



Input to the system consists of the perceptual encoding (orthographic or phonological) of one word of a sentence at a time

Besides the new theory-building, there still remains considerable interest in the previous version of the cognitive architecture (3CAPS), namely the form that preceded the brain activation modeling, accounts of working memory constraints and individual differences. In a commentary soon to appear in *Psychological Review*, Just and Varma describe how the symbolic and connectionist mechanisms within the hybrid 3CAPS architecture combine to produce a processing style that provides a good match to human sentence comprehension and other types of high-level cognition. (This article should not be confused with the manuscript describing the 4CAPS theory). The article relates the properties of 3CAPS to other connectionist, symbolic, and hybrid systems.

On another theoretical front, we have written an overview article in *Current Opinion in Neurobiology* that characterizes working memory and executive function (Carpenter, Just, & Reichle, 2000). The paper reviews the neuro-imaging literature and argues against a localization view of working memory and executive function. We argue that the existing meta-analyses of empirical data on verbal and spatial working memory and specific empirical studies addressing the localization hypothesis have failed to support localization. In its place, we suggest the usefulness of the perspective of dynamic systems theory to understand aspects of the generativity and organization of human cognition.

ONR-supported Papers published or In Press in Refereed Journals:

Carpenter, P. A., Just, M. A., Keller, T. A., Eddy, W. F., & Thulborn, K. R. (1999). Time course of fMRI-activation in language and spatial networks during sentence comprehension. *NeuroImage, 10*, 216-224.

Carpenter, P. A., & Just, M. A. (1999). Modeling the mind: Very High-field fMRI-activation during cognition. In K. R. Thulborn (Issue Ed.), *Topics in magnetic resonance imaging, 10*, 16-36. Philadelphia, PA: Lippincott, Williams, & Wilkins.

Carpenter, P. A., & Just, M. A. (1999). Computational modeling of high-level cognition versus hypothesis testing. In R. J. Sternberg (Ed.), *The nature of cognition* (pp. 245-294). Cambridge, MA: MIT Press.

Carpenter, P. A., Just, M. A., Keller, T. A., Eddy, W. F., & Thulborn, K. R. (1999). Graded functional activation in the visuo-spatial system with the amount of task demand. *Journal of Cognitive Neuroscience, 11*, 9-24.

Carpenter, P. A., Just, M. A., & Reichle, E. D. (2000). Working memory and executive function: Evidence from neuroimaging. *Current Opinion in Neurobiology, 10*, 195-199.

Diwadkar, V. A., Carpenter, P. A., & Just, M. A. (2000). Collaborative activity between parietal and dorso-lateral prefrontal cortex in dynamic spatial working memory revealed by fMRI. *NeuroImage, 12*, 85-99.

Just, M. A., & Varma, S. (in press). A hybrid architecture for working memory. *Psychological Review.*

Just, M. A., Carpenter, P. A., Maguire, M., Diwadkar, V., McMains, S. (in press). Mental rotation of objects retrieved from memory: An fMRI study of spatial processing. *Journal of Experimental Psychology: General.*

Just, M. A., Carpenter, P. A., & Varma, S. (1999). Computational modeling of high-level cognition and brain function. *Human Brain Mapping. 8*, 128-136.

Reichle, E. D., Carpenter, P. A., & Just, M. A. (2000). The neural basis of strategy and skill in sentence-picture verification. *Cognitive Psychology.40,* 261-295.

Just, M. A., Carpenter, P. A., Maguire, M., Diwadkar, V., McMains, S. (2001). Mental rotation of objects retrieved from memory: An fMRI study of spatial processing. *Journal of Experimental Psychology: General, 130*, 493-504.

Just, M. A., & Varma, S. (in press). A hybrid architecture for working memory. *Psychological Review.*

Symposium at Psychonomics 99 in Los Angeles. One of us (MJ) organized a symposium on the contributions that functional brain imaging is making to the understanding of high level cognition. The formal title was "Functional Brain Imaging and Higher Level Cognition." The presenters were Jordan Grafman, Ed Smith, Morton Gernsbacher, Dan Schacter, and Marcel Just.

Invited Presentations by Co-PI's during the tenure of the current ONR grant

Cognitive loading and the future military. Invited presentation at the Cognitive Sciences Workshop sponsored by the Science Applications International Corporation (SAIC), January 8-9, 1998, Strategic Assessment Center, McLean, Virginia.

Working memory and working brain: Computational and fMRI studies of cognition. Invited presentation at the University of Pittsburgh, Western Psychiatric Institute and Clinic, February 19, 1998, Pittsburgh Pennsylvania.

Modeling neural function and high-level cognition. Invited presentation at CNBC/ICN Workshop, Mellon Institute, Carnegie Mellon University, March 26, 1998, Pittsburgh, Pennsylvania.

fMRI and higher cognitive functions. Invited presentation at the First Annual Meeting of the NICHD/NIDCD Collaborative Programs of Excellence in Autism (CPEA), June 14-15, 1998, Washington DC.

Recovery of language-related brain function after aphasia. Invited presentation at the James S. McDonnell Foundation Program in Cognitive Rehabilitation, September 10-12, 1998, St. Louis, Missouri.

fMRI and the Neuro-architecture of cognition. Invited presentation at the National Institute of Mental Health "Cognitive Neuroimaging Research: Design and Interpretation Meeting", September 13-15, 1998, Rockville, Maryland.

Cognitive load distribution in normal and autistic individuals. Invited presentation at the 29th Carnegie Symposium on Cognition, "Mechanisms of Cognitive Development: Behavioral and Neural Perspectives", October 11, 1998, Pittsburgh, Pennsylvania.

Modeling cognitive systems with artificial intelligence & fMRI. Invited presentation at BrainMap '98: Human Brain Mapping and Modeling, December 7, 1998, San Antonio, Texas.

Language in the brain: fMRI studies of sentence comprehension. Colloquium presented at the University of Pittsburgh, Department of Linguistics, April 7, 1999, Pittsburgh, Pennsylvania.

fMRI and the neuro-architecture of cognition: studies of sentence comprehension. Colloquium presented at the Center for Cognitive Sciences, University of Minnesota, May 13, 1999, Minneapolis, Minnesota.

Language in the brain: fMRI studies of sentence comprehension. Invited presentation at the International Conference on Basic Mechanisms of Language and Language Disorders, University of Leipzig, September 30, 1999, Leipzig, Germany.

Dynamic cortical systems subserving cognition: What fMRI reveals about (some) secrets of the mind. Colloquium, Department of Psychology, November 8, 1999, Carnegie Mellon University, Pittsburgh, Pennsylvania.

fMRI and the neuro-architecture of cognition. Presented at a Symposium held at the Psychonomics Society, November 19-21, 1999, Los Angeles, California

Imaging the brain, visualizing the future. Presented at the Carnegie Mellon Board of Trustees Executive Committee Meeting, December 13, 1999, University Center, Pittsburgh, Pennsylvania

fMRI and the neuro-architecture of cognition. Presented at the ONR Cognitive Architecture Meeting, March 31-April 1, 2000, Carnegie Mellon University, Pittsburgh Pennsylvania.

4CAPS: Cortical Capacity-Constrained Concurrent Activation-based Production System. Presented at the ONR Cortical Modeling Conference, June 5, 2000, Baltimore, Maryland.

Brain activation during sentence comprehension in high-functioning autistic subjects. Presented at the Collaborative Program of Excellence in Autism (CPEA) Meeting, September 25-29, 2000, Denver, Colorado.

fMRI studies of the architecture of language comprehension. Keynote address presented at the 64th Conference of the Japanese Psychological Association, November 6-8, 2000, Kyoto Japan.

Spatial cognition: fMRI evidence on the architecture of the mind. Keynote address presented at the 64th Conference of the Japanese Psychological Association, November 6-8, 2000, Kyoto Japan.

The brain-activation dynamics underlying fluid intelligence. Invited Paper at the 1st Annual Conference of the International Society for Intelligence Research (ISIR), November 30, 2000, Cleveland, Ohio.

fMRI and the neuro-architecture of cognition. Presented at the T. J. Watson Research Center, January 31, 2001, Yorktown Heights, New York

Brain activation during sentence comprehension in high-functioning autistic subjects. Presented at the Annual Meeting of the Collaborative Programs of Excellence in Autism (CPEA), Yale Child Study Center, April 30 – May 2, 2001, New Haven, Connecticut.

Using brain imaging to measure cognitive workload. Presented at the CMU/GM Collaborative Lab Mini Retreat, Electrical & Computer Engineering Department, August 20, 2201, Pittsburgh, Pennsylvania.

Grant-related Posters (in collaboration with post-doctoral fellows)

Ventral and dorsal cortical systems collaborate during visual object recognition. Poster presented at the Psychonomics Society Meeting, November 19-21, 1999, Los Angeles, California

The cortical bases of strategy and skill in sentence-picture verification. Poster presented at the Psychonomics Society Meeting, November 19-21, 1999, Los Angeles, California

Cognitive workload and cortical activation in problem solving. Poster presented at the Cognitive Neuroscience Society Meeting, San Francisco, California, April 9-12, 2000.

The cortical basis of visual object recognition: Evidence of dorsal and ventral collaboration. Poster presented at the Cognitive Neuroscience Society Meeting, San Francisco, California, April 9-12, 2000.

Cognitive workload and cortical activation in problem solving. Poster presented at the Cognitive Neuroscience Society Meeting, San Francisco, California, April 9-12, 2000.

The cortical basis of visual object recognition: Evidence of dorsal and ventral collaboration. Poster presented at the Cognitive Neuroscience Society Meeting, San Francisco, California, April 9-12, 2000.

Cortical systems supporting figural encoding, maintenance, and rotation. Poster to be presented at the Psychonomics Society Meeting, November 15-18, 2001, Orlando, Florida.

An fMRI comparison of haptic versus visual imagery. Poster to be presented at the Psychonomics Society Meeting, November 15-18, 2001, Orlando, Florida.

Awards/Honors:

NIMH Senior Scientist Award: 1997 - 2002 (PC)

NIMH Senior Scientist Award: 1997 - 2002 (MJ)

Outstanding Research Award from ABOARD (Advisory Board on Autism and Related Diseases), June 26, 2001. (MJ)

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

During the current grant, considerable progress was made in relating fMRI-measured activation during high-level spatial thinking to the properties of the cognitive architecture in three areas:
(1) empirical studies of fMR-imaging during various types of spatial thinking,
(2) developments of methodological tools for fMRI research, and
(3) development of a theory and a computational modeling system to relate cognitive processing to the underlying large-scale cortical networks.

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